Superlensing Plano-Convex-Microsphere(PCM) lens for direct laser nano marking and beyond

Yan, Bing; Yue, Liyang; Monks, James; Yang, Xibin; Xiong, Daxi; Jiang, Chunlei; Wang, James

Optics Letters

DOI:
10.1364/OL.380574

Published: 01/03/2020

Superlensing Plano-Convex-Microsphere (PCM) lens for direct laser nano marking and beyond

BING YAN,[1,2] LIYANG YUE,[1] JAMES NORMAN MONKS,[1] XIBIN YANG,[2,4] DAXI XIONG,[2] CHUNLEI JIANG,[3] ZENGBO WANG[1,*]

[1] School of Computer Science and Electronic Engineering, Bangor University, Dean Street, Bangor, Gwynedd, LL57 1UT, UK
[2] Center of Optics Health, Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences, No. 88 Keling Street, Suzhou Jiangsu, 215163, China
[3] College of Electrical and Information Engineering, Northeast Petroleum University, Daqing, 163318, China
[4]e-mail: yangxb@sibet.ac.cn
**Corresponding author: z.wang@bangor.ac.uk*

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

A high-performance all-dielectric lens, formed by integrating a conventional Plano-Convex lens with a high-index Microsphere lens (PCM), was developed for far-field super-resolution applications. The PCM lens features a theoretical resolution of ~λ/2.5 in air with a working distance ~2 μm away from the lens. When combined with femtosecond laser, the actual patterning resolution can reach ~λ/3.5. The unusual focusing properties were theoretically and experimentally verified, and direct laser nano writing of arbitrary patterns and nanostructures on various substrates were demonstrated. This work can be naturally extended to other super-resolution applications including imaging, sensing, trapping and more, with potentials of developing next generation low-cost direct laser nano marking machine and super-resolution imaging nanoscope.

http://dx.doi.org/10.1364/OL.99.099999

Laser has been recognized as one of the most extensively used tools for micro/nano-patterning. Complicated structures can be precisely generated through a noncontact and maskless laser direct-writing. However, the key challenge of laser processing to produce extremely small features is the optical diffraction limit [1]. To overcome such difficulty, various laser-based techniques were emerged for sub-diffraction nano-texturing, such as nearfield scanning optical microscope (NSOM) patterning [2,3], laser combination with scanning probe microscopy (SPM) tip patterning [2,4], plasmonic lithography [5], laser thermal lithography (ITL) [6], interference lithography [7,8], as well as multiphoton absorption lithography [9,10], etc. However, these techniques were limited in laboratory stage due to their low throughput and sophisticated control system.

Recently, using dielectric microsphere as a nearfield lens for super-resolution nano imaging and fabrication has attracted great interests. The optical phenomenon knowns as photonic nanojet can contribute to laser beam focusing to break the diffraction limit [11-13]. Researchers have achieved sub-diffraction features (~λ/3) through laser-induced particle lens technique [14,15]. In order to increase the throughput, contacting particle lens arrays (CPLA) technique was also introduced. This method employs a monolayer close-packed particle-lens array to split laser beam into multiple enhanced focal spots to generate parallel nano-features over large area [16-18]. Guo et al., on this basis, has improved and innovated a kind of arbitrary-shaped patterning technique by an adjustable angular incident laser beam [19].

Although CPLA has been proven to be a simple and highly productive strategy for nano-fabrication on various materials, there are some inevitable limitations. The target substrate for preparing preliminary self-assembly monolayer has to be hydrophilic which implies the inadaptability of hydrophobic surface [20]. Furthermore, the ejection of microspheres generally happens after a single laser shot, which may due to thermal expansion of substrate caused by laser absorption [21]. Therefore, the substrate dependency and non-reusable factor make it impossible for industry use. Several techniques were proposed to circumvent these issues, usually by transferring CPLA to transparent host media [22-24]. Although multi-pulse processing is feasible by this method, the series of techniques are still lack of reliability and cannot produce user-defined arbitrary nanostructures. Therefore, there is a strong need to further develop this technique to meet industry processing requirement.

In order to realize accurate and smooth scan patterning process, a gap between focusing lens and sample is a necessary condition. Contrariwise, contact-mode may result in dragging issues due to lens-sample friction, which can lead distortion of final patterns. In addition, unintentional scratches on delicate samples may also be generated. Most researches have studied the microsphere lens patterning technique based on nearfield mode that is contact or within an incident wavelength distance. Recently, manipulation of single microsphere lens by laser trapping and tip-based scanning techniques were demonstrated for complex nano-pattern processing [25,26]. They were both worked in the near-field modes, either limited to liquid environment (laser trapping) or involving sophisticated and costly near-field tip control system. We wish to develop a far-field, low-cost, super-resolution microsphere scanning writing system for direct laser writing of arbitrary nano patterns, which can be further extended to super-resolution imaging and sensing applications.

In this paper, we report a major step forward in laser direct patterning system that can perform large-area subwavelength surface processing with user-defined patterns. A new superlens design, namely a compound lens consisting of a Plano-Convex lens and a Microsphere lens (PCM), was proposed. The PCM superlens can be implemented as an optical probe to generate subwavelength focusing at micrometer distance. With the assist of side-view monitoring system and high-resolution nano-stage, we can achieve precise control and monitor of the working distance (WD) between probe and sample during scan patterning process. Meanwhile, the performance of PCM lens at different WD was theoretically and experimental evaluated. The capability of arbitrary pattern fabrication was realized. It is an objective-free, low-cost, high efficient and flexible system with high completion for large-area sub-wavelength nano-patterning, which will satisfy the growing industrial demands in laser nano-patterning.

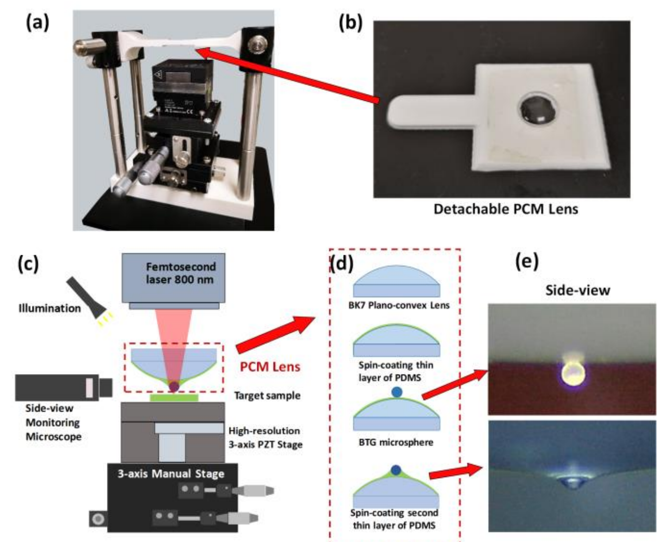

Fig. 1. PCM lens and system setup for laser nano-patterning. (a) Photograph of actual system setup. (b) Photograph of actual detachable PCM lens module. (c) Schematic of the PCM nano-patterning system. (d) Fabrication of PCM lens. (e) Side view of PCM lens.

The experimental setup is illustrated in Fig. 1(a) and (c). The supporting frame was made of 3D printed structures and metal struts to install lens and stages. A Barium Titanium Glass (BTG) microsphere (BTGMS, Cospheric) with diameter of 50 μm was aligned and attached onto PDMS SYLGARD 184, DOW CORNING) or UV glue (NOA63, Noland Adhesive) pre-coated curved surface of a BK7 Plano-Convex lens (LA1700, Thorlabs). A second thin layer of PDMS or UV glue was then applied to form partially encapsulation of BTG microsphere by spin-coating at 2000 rpm for 1 minute [Fig. 1(d)]. This results in the formation of a probe-like Plano-Convex microsphere (PCM) lens, where a single microsphere slightly extruding out [Fig. 1(e)]. Afterwards, the PCM lens was bonded onto a 3D printed lens holder to build a detachable PCM lens module [Fig. 1(b)]. A manual 3-axis stage was used for coarsely adjusting target sample. A long working distance zoom lens was placed horizontally at side for monitoring the gap between microsphere tip and samples. The light sources were generated by femtosecond laser consisting of a Ti:Sapphire oscillator (Spectra Physics Tsunami) and a regenerative amplifier (Spectra Physics Spitfire) which provides 800 nm wavelength, 100 fs pulse duration and 5 KHz repetition rate. The beam diameter projected at the PCM lens incident plane was ~200 μm.

The scanning was performed using a high-resolution nano-stage (P-611.3 NanoCube, Physik Instrumente), with 1 nm resolution in the XYZ direction, and a travel range of 100 μm. In our experiments, the PCM lens was kept static and the underlying nano-stage moved and scanned the samples across the PCM lens. The laser processing was automatically undertaken at the synchronization of laser and nano-stage through in-house developed GCS code. Samples including silicon wafer, nickel and Au thin film coated glass were tested.

To understand focusing characteristics of the PCM lens, computational modelling was performed using in-house developed code based on physical optics. A planar wave (800 nm, x-polarized) propagates (along z-axis) through a 50 μm Barium Titanate Glass (BTG) microsphere (n_p=1.9) partially encapsulated by PDMS material (n_m=1.4) to imitate PCM lens in the experiment. Fig. 2(a) shows the calculated optical field distribution in YZ-plane. It reveals that the electric field intensity exhibits elongated shape and diverges with distance. The electric field intensity was greatly enhanced (~2000 times) at a 9.14 μm distance away from microsphere bottom boundary and intensity drops quickly onwards. Fig. 2(b) illustrates the field profiles along y direction at different WD. We observed multi-peak focusing phenomena before the light convergence and significant side-peak occurs around 7 μm distance. The focal spot size with respect to the distances was revealed in Fig. 2(c). The calculated full-width at half-maximum (FWHM) starts from 200 nm at boundary of microsphere, then gradually arises to 670 nm as the distance increases to 11 μm, afterwards it reaches at micro-scale due to light divergence. The super-resolution (λ/2<400 nm) is found for distances within 6 μm measured from the bottom of PCM lens.

To verify the theoretical analysis, experiments were carried out by a femtosecond 800 nm wavelength laser with fluence of 9.5±0.2 mJ/cm^2. A blank silicon wafer was initially elevated to moderately contact with the PCM lens by nano-stage, and then lowered down with 1 μm step until 16 μm apart. Laser was triggered at each WD and patterned features are shown in Fig. 2(d). Fig. 2(e)-(p) are the enlarged SEM images at WD from 2 μm to 13 μm. There was no feature observed at distances of 1 μm and 14~16 μm, it is because of the low field enhancement or large focal spot in these region resulting in the power density less than the silicon damage threshold, as simulation result showing in Fig. 2(c). At WD=2 μm, the theoretical super-resolution focus spot size is 320 nm [λ/2.50, Fig. 2(c)]. In experiments, we however achieved smaller feature size down to 230 nm [λ/3.48, Fig. 2(e)], this is due to the nonlinear multiphoton absorption effect when femtosecond laser pulse interacts with materials [27]. The feature size increased gradually afterwards, to around 1 micron at WD=4 μm. It is noted that distances at 6, 7 and 8 μm distance, features exhibited not only single hole, but also outer ring patterns simultaneously [Fig. 2(d), (i-k)]. This may be determined by the multiple peaks effect, which is consistent with previously discussed theoretical simulation results, shown in Fig. 2(b). Therefore, high quality laser marking should avoid such circumstances. Meanwhile, the sharpest and roundest hole pattern was found at the distance of 9 μm Fig. 2(l), which can be seen as processing focus point. Furthermore, Fig. 2(p) shows a very shallow and unclear dot generated at 13 μm away from the PCM lens. In general, the experimental results agreed well with the simulation model, and smallest feature size is mainly determined by the PCM lens WD and laser power density.

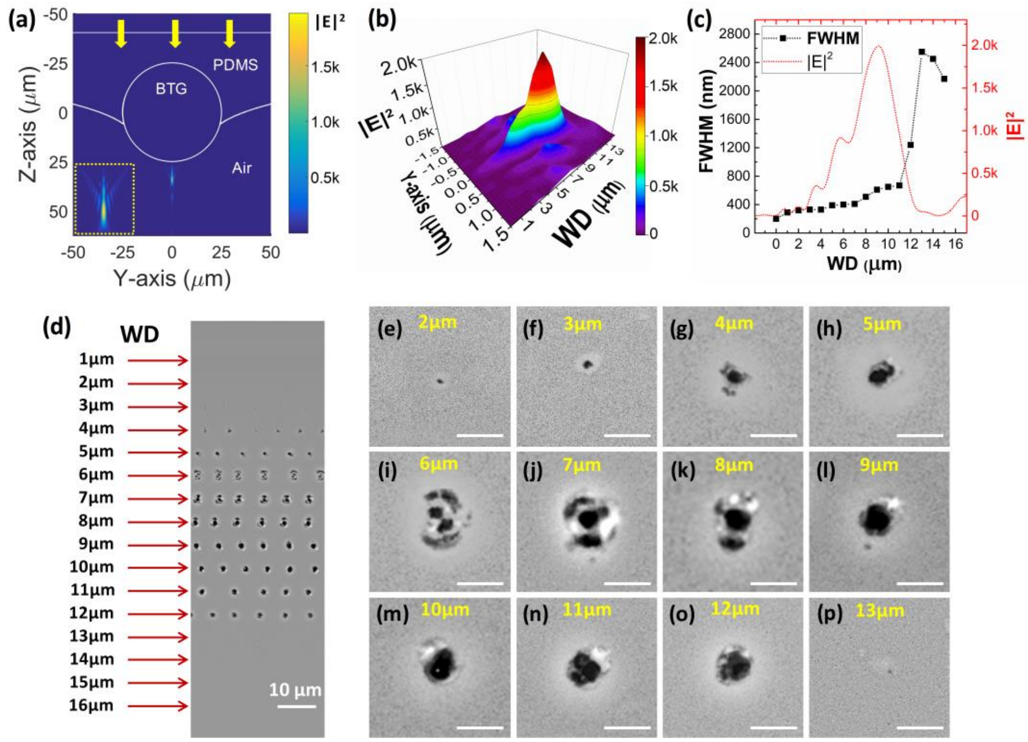

Fig. 2. Modelling of PCM lens focusing properties and experimental results of femtosecond laser machined feature size against WD. (a) Electric field intensity $|E|^2$ distribution of PCM lens across the YZ incident plane, the inset shows the enlarged view of focusing area. (b) Field distribution along y-axis and (c) FWHM and $|E|^2$ enhancement at different WD. (d) Femtosecond laser patterned feature at WD from 1 to 16 μm, and enlarged SEM images (e)-(p) at 2-13 μm distances, scale bar in (e)-(p) are 2 μm.

In scanning patterning mode, laser was synchronized with the maneuver of piezo nano-stage by in-house developed controlling code, which controlled laser beam on and off while sample moving to realize accurate positioning machining. A blank silicon wafer was scanned over an area in non-contact mode with 2-μm distance under PCM lens, thus avoiding the undesired scratches and distorted pattern from fiction between lens and samples. Here, we presented two scanning modes: point-by-point and continuous mode. In the point-by-point mode, the laser emits a pulse when nano-stage completes a step. Therefore, the pattern outline is formed by dots with certain interval, as shown in Fig. 3(a) and (b). Possibly due to system vibration and fluctuations (e.g. laser fluence and scanning system) during experiments, the obtained dots have a size variation ranging from 230 nm to 350 nm. On the other hand, Fig. 3(c) and (d) show the continuously processed line can be generated by keeping the laser constantly on during sample moving. In this case the line size is about 300-350 nm.

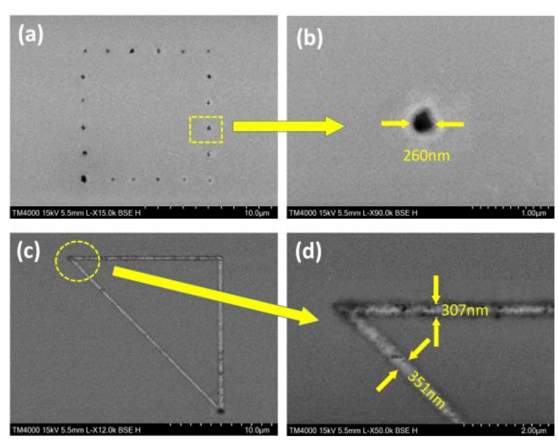

Fig. 3. Scanning patterning by (a-b) point-by-point and (c-d) continuous mode.

Furthermore, it is important to know that the proposed system is not limited to fabricate simple line and dot patterns, but also flexible to write user-defined complex patterns. Arbitrary pictures can be directly converted into nano-stage recognizable GCS code by self-developed Java program. Therefore, the sample's moving path followed the exact shape from original pictures. The capability of writing complex arbitrary patterns was evaluated, shown in Fig. 4. Meanwhile, we have extended this method to other materials, such as nickel [Fig. 4(d)] and glass substrate [Fig. 4(e, f)]. The average processing resolution on glass substrate was measured as 354 nm. Compared to CPLA technique for simple structure in limited area, our system provides a more flexible way in large-area patterning. Moreover, this technique can be further developed by using shorter wavelength laser such as UV laser (355 nm) to improve the patterning resolution down to about 100 nm. The PCM lens can naturally be extended to other super-resolution applications including nano-imaging, sensing, trapping and manipulation of nano-objects and samples [28,29].

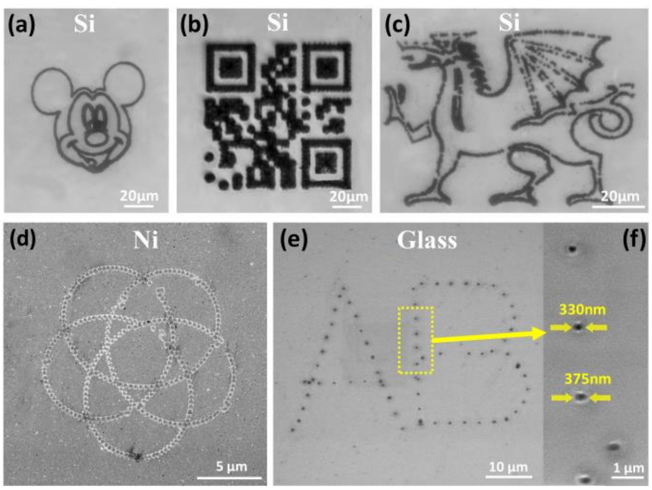

Fig. 4. Arbitrary pattern on different sample surfaces. On silicon wafer (a) mickey mouse, (b) Bangor University website QR code, (c) Welsh Dragon. (d) Guilloche pattern on nickel substrate, (e) letters on glass substrate, (f) enlarge image of highlight area in (e).

In summary, we have proposed and demonstrated a new PCM superlens that can be operated in farfield scanning manner to effectively process complex arbitrary patterns in sub-wavelength scale. The effect of non-contact patterning was evaluated theoretically and experimentally at different WD. The individual subwavelength features size as small as 230 nm (λ/3.48) – 350 nm (λ/2.29) can be directly fabricated. The large-area complex structures with arbitrary shapes can easily generated. Meanwhile, the reliability and repeatability were significantly improved compared to other microsphere-based laser fabrication techniques. The development is low-cost and compatible with any existing laser marking system to enhance their pattering resolution.

Funding. Center for Photonics Expertise (CPE), European Regional Development Fund (ERDF) (81400); Knowledge Economy Skills Scholarship (KESS2) (BUK289).

References

1. E. Abbe, Arch. für mikroskopische Anat. **9**, 413 (1873).
2. T. C. Chong, M. H. Hong and L. P. Shi, Laser Photon. Rev. **4**, 123 (2010).
3. E. Betzig, J. K. Trautman, R. Wolfe, E. M. Gyorgy, P. L. Finn, M. H. Kryder and C. H. Chang, Appl. Phys. Lett. **61**, 142 (1992).
4. Y. F Lu, Z. H. Mai, Y. W. Zheng and W. D. Song, Appl. Phys. Lett. **76**, 1200 (2000).
5. Z. W. Liu, Q. H. Wei and X. Zhang, Nano lett. **5**, 957 (2005).
6. L. P. Shi and T. C. Chong, J. Nanosci. Nanotechnol. **7**, 65 (2007).
7. M. Bieda, M. Siebold and A. F. Lasagni, Appl. Surf. Sci. **387**, 175 (2016).
8. R. Ahmed, A. K. Yetisen, A. El Khoury and H. Butt, Nanoscale **9**, 266 (2017).
9. S. Kawata, H. B. Sun, T. Tanaka and K. Takada, Nature **412**, 697 (2001).
10. M. Aeschlimann, M. Bauer, D. Bayer, T. Brixner, F. J. G. De Abajo, W. Pfeiffer and F. Steeb, Nature **446**, 301 (2007).
11. Z. Chen, A. Taflove and V. Backman, Opt. Express **12**, 1214 (2004).
12. S. Lecler, Y. Takakura and P. Meyrueis, Opt. lett. **30**, 2641 (2005).
13. Y. F. Lu, L. Zhang, W. D. Song, Y. W. Zheng and B. S. Luk'Yanchuk, J. Exp. Theor. Phys. Lett. **72**, 457 (2000).
14. E. Mcleod and C. B. Arnold, Nature Nanotechnol. **3**, 413 (2008).
15. E. McLeod and C. B. Arnold, Opt. Express **17**, 3640 (2009).
16. S. M. Huang, M. H. Hong, B. Lukiyanchuk and T. C. Chong, Appl. Phys. A **77**, 293 (2003).
17. Z. B. Wang, M. H. Hong, B. S. Luk'yanchuk, Y. Lin, Q. F. Wang and T. C. Chong, J. Appl. Phys. **96**, 6845 (2004).
18. Z. B. Wang, M. H. Hong, B. S. Luk'yanchuk, S. M. Huang, Q. F. Wang, L. P. Shi and T. C. Chong, Appl. Phys. A **79**, 1603 (2004).
19. W. Guo, Z. B. Wang, L. Li, D. J. Whitehead, B. S. Luk'yanchuk and Z. Liu, Appl. Phys. Lett. **90**, 243101 (2007).
20. N. Denkov, O. Velev, P. Kralchevski, I. Ivanov, H. Yoshimura and K. Nagayama, Langmuir **8**, 3183 (1992).
21. M. Mosbacher, H. J. Münzer, J. Zimmermann, J. Solis, J. Boneberg and P. Leiderer, Appl. Phys. A **72**, 41 (2001).
22. C. O'Connell, R. J. Sherlock and T. J. Glynn, Opt. Eng. **49**, 014201 (2010).
23. A. Khan, Z. Wang, M. A. Sheikh, D. J. Whitehead and L. Li, J. Phys. D: Appl. Phys. **43**, 305302 (2010).
24. A. Khan, Z. Wang, M. A. Sheikh, D. J. Whitehead and L. Li, Appl. Surf. Sci. **258**, 774 (2011).
25. A. Shakhov, A. Astafiev, A. Gulin and V. Nadtochenko, ACS Applied Mater. Inter. **7**, 27467 (2015).
26. Y. Wen, H. Yu, W. Zhao, F. Wang, X. Wang, L. Liu and W. J. Li, IEEE Transactions on Nanotechnology **18**, 226 (2019).
27. S. S. Harilal, J. R. Freeman, P. K. Diwakar, and A. Hassanein, in *Laser-Induced Breakdown Spectroscopy* (Springer, 2014), p. 143.
28. Z. Wang, W. Guo, L. Li, B. Luk'yanchuk, A. Khan, Z. Liu, Z. Chen, and M. Hong, Nat. Commun. **2**, 218 (2011).
29. B. S. Luk'yanchuk, R. Paniagua-Dominguez, I. Minin, O. Mini, and Z. B. Wang, Opt. Mater. Express **7**, 1820-1847 (2017).

References

1. E. Abbe, "Beiträge zur Theorie des Mikroskops und der mikroskopischen Wahrnehmung," Arch. für mikroskopische Anat. **9**(1), 413-418 (1873).
2. T. C. Chong, M. H. Hong and L. P. Shi, "Laser precision engineering: from microfabrication to nanoprocessing," Laser Photon. Rev. **4**(1), 123-143 (2010).
3. E. Betzig, J. K. Trautman, R. Wolfe, E. M. Gyorgy, P. L. Finn, M. H. Kryder and C. H. Chang, "Near-field magneto-optics and high density data storage," Appl. Phys. Lett. **61**(2), 142-144 (1992).
4. Y. F Lu, Z. H. Mai, Y. W. Zheng and W. D. Song, "Nanostructure fabrication using pulsed lasers in combination with a scanning tunneling microscope: mechanism investigation," Appl. Phys. Lett. **76**(9), 1200-1202 (2000).
5. Z. W. Liu, Q. H. Wei and X. Zhang, "Surface plasmon interference nanolithography," Nano lett. **5**(5), 957-961 (2005).
6. L. P. Shi and T. C. Chong, "Nanophase change for data storage applications," J. Nanosci. Nanotechnol. **7**(1), 65 (2007).
7. M. Bieda, M. Siebold and A. F. Lasagni, "Fabrication of sub-micron surface structures on copper, stainless steel and titanium using picosecond laser interference patterning," Appl. Surf. Sci. **387**, 175-182 (2016).
8. R. Ahmed, A. K. Yetisen, A. El Khoury and H. Butt, "Butt, H. Printable ink lenses, diffusers, and 2D gratings," Nanoscale **9**(1), 266-276 (2017).
9. S. Kawata, H. B. Sun, T. Tanaka and K. Takada, "Finer features for functional microdevices," Nature **412**(6848), 697 (2001).
10. M. Aeschlimann, M. Bauer, D. Bayer, T. Brixner, F. J. G. De Abajo, W. Pfeiffer and F. Steeb, "Adaptive subwavelength control of nano-optical fields," Nature **446**(7133), 301 (2007).
11. Z. Chen, A. Taflove and V. Backman, "Photonic nanojet enhancement of backscattering of light by nanoparticles: a potential novel visible-light ultramicroscopy technique," Opt. Express **12**(7), 1214-1220 (2004).
12. S. Lecler, Y. Takakura and P. Meyrueis, "Properties of a three-dimensional photonic jet," Opt. lett. **30**(19), 2641-2643 (2005).
13. Y. F. Lu, L. Zhang, W. D. Song, Y. W. Zheng and B. S. Luk'Yanchuk, "Laser writing of a subwavelength structure on silicon (100) surfaces with particle-enhanced optical irradiation," J. Exp. Theor. Phys. Lett. **72**(9), 457-459 (2000).
14. E. Mcleod and C. B. Arnold, "Subwavelength direct-write nanopatterning using optically trapped microspheres," Nature Nanotechnol. **3**(7), 413 (2008).
15. E. McLeod and C. B. Arnold, "Array-based optical nanolithography using optically trapped microlenses," Opt. Express **17**(5), 3640-3650 (2009).
16. S. M. Huang, M. H. Hong, B. Lukiyanchuk and T. C. Chong, "Nanostructures fabricated on metal surfaces assisted by laser with optical near-field effects" Appl. Phys. A **77**(2), 293-296 (2003).
17. Z. B. Wang, M. H. Hong, B. S. Luk'yanchuk, Y. Lin, Q. F. Wang and T. C. Chong, "Angle effect in laser nanopatterning with particle-mask," J. Appl. Phys. **96(**11), 6845-6850 (2004).
18. Z. B. Wang, M. H. Hong, B. S. Luk'yanchuk, S. M. Huang, Q. F. Wang, L. P. Shi and T. C. Chong, "Parallel nanostructuring of GeSbTe film with particle mask," Appl. Phys. A **79**(4), 1603-1606 (2004).
19. W. Guo, Z. B. Wang, L. Li, D. J. Whitehead, B. S. Luk'yanchuk and Z. Liu, "Near-field laser parallel nanofabrication of arbitrary-shaped patterns," Appl. Phys. Lett. **90**(24), 243101 (2007).
20. N. Denkov, O. Velev, P. Kralchevski, I. Ivanov, H. Yoshimura and K. Nagayama, "Mechanism of formation of two-dimensional crystals from latex particles on substrates," Langmuir **8**(12), 3183-3190 (1992).
21. M. Mosbacher, H. J. Münzer, J. Zimmermann, J. Solis, J. Boneberg and P. Leiderer, "Optical field enhancement effects in laser-assisted particle removal," Appl. Phys. A **72**(1), 41-44 (2001).
22. C. O'Connell, R. J. Sherlock and T. J. Glynn, "Fabrication of a reusable microlens array for laser-based structuring," Opt. Eng. **49**(1), 014201 (2010).
23. A. Khan, Z. Wang, M. A. Sheikh, D. J. Whitehead and L. Li, J. "Parallel near-field optical micro/nanopatterning on curved surfaces by transported micro-particle lens arrays," Phys. D: Appl. Phys. **43**(30), 305302 (2010).
24. A. Khan, Z. Wang, M. A. Sheikh, D. J. Whitehead and L. Li, "Laser micro/nano patterning of hydrophobic surface by contact particle lens array," Appl. Surf. Sci. **258**(2), 774-779 (2011).
25. A. Shakhov, A. Astafiev, A. Gulin and V. Nadtochenko, "Femtosecond nanostructuring of glass with optically trapped microspheres and chemical etching," ACS Applied Mater. Inter. **7**(47), 27467-27472 (2015).
26. Y. Wen, H. Yu, W. Zhao, F. Wang, X. Wang, L. Liu and W. J. Li, "Photonic Nanojet Sub-Diffraction Nano-Fabrication with in situ Super-Resolution Imaging," IEEE Transactions on Nanotechnology **18**, 226-233 (2019).
27. S. S. Harilal, J. R. Freeman, P. K. Diwakar, and A. Hassanein, "Femtosecond laser ablation: Fundamentals and applications," in Laser-Induced Breakdown Spectroscopy, S. Musazzi, and U. Perini, ed. (Springer, 2014), pp. 143-166.
28. Z. Wang, W. Guo, L. Li, B. Luk'yanchuk, A. Khan, Z. Liu, Z. Chen, and M. Hong, "Optical virtual imaging at 50 nm lateral resolution with a white-light nanoscope," Nat. Commun. **2**, 218 (2011).
29. B. S. Luk'yanchuk, R. Paniagua-Dominguez, I. Minin, O. Mini, and Z. B. Wang, "Refractive index less than two: photonic nanojets yesterday, today and tomorrow," Opt. Mater. Express **7**(6), 1820-1847 (2017).